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Conceptualization of an artificial intelligence-assisted tutoring system for teaching technical drawing skills to undergraduate students

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Abstract

In design education, technical drawing training requires a large amount of resources. The aim of this paper is to propose a concept for an artificial intelligence-based tutoring system that partly automates technical drawing education. The educational needs of the students are defined via an error analysis of 100 corrected drawing exercises and the definition of 3 error clusters with 134 different error types. Three sub-concepts with a collection of training exercises are proposed for the tutoring system to mitigate these errors. The resulting concept is validated by a survey with 29 students.

Keywords: design education, artificial intelligence (AI), design skills, computational design methods, technical drawings

1. Introduction

Technical drawings are the most common form of formalized component description in engineering and a central element in the development of mechanical components (Garland et al., 2017; Sampaio, 2018). They serve as an important means of communication between different disciplines and groups of people within organizations (Lille, 2013; Barr, 2004; Kosse, 2005). Despite the progress of digitization and the widespread use of virtual CAD data in mechanical engineering, technical drawings are still widely used in industry (Moreno-García et al., 2019). For this reason, engineers must have the ability to create, read, and understand technical drawings. Making such drawings therefore remains an important skill for engineers. When teaching technical drawing to undergraduate engineering students, there is only limited opportunity to pay individual attention to students. This can consume considerable amounts of time, for example due to the correction of test certificates. Students are unable to quickly obtain feedback, making it difficult to achieve rapid learning effects (Rahmandad et al., 2009). An online tutoring system with short feedback loops that assists the students while they learn technical drawing skills might have the potential to deal with this problem in design education. In this context, artificial intelligence (AI) has the potential to process image data such as technical drawings and there is thus potential for an artificially intelligent tutoring system to perform the evaluation of technical drawings (Moreno-García et al., 2019). This is indeed a declared aim of the IKILeUS project, in which this research is based. IKILeUS is the abbreviation for Integrated Artificial Intelligence in Teaching at the University of Stuttgart and brings together various projects aimed at improving teaching with artificial intelligence. In order to define an artificially intelligent tutoring system for technical drawings within the IKILeUS project, it is necessary to define the educational needs and a suitable concept for the tutoring system.
With that in mind, this publication aims to perform a needs analysis for an artificially intelligent tutoring system that addresses the problems of undergraduate students regarding technical drawing education. A

concept for an artificially intelligent tutoring system is then derived on the basis of these needs. The concept is subsequently evaluated by means of a survey conducted with undergraduate students.

2. Research scope and method

The role of the tutoring system in the didactic context can be categorised according to the principle of "constructive alignment" (Biggs and Tang 2011). The learning objective is the ability to create and understand technical drawings. This is tested by an examination with drawing tasks on individual parts and assemblies. The learning method for preparing this examination essentially consists of teaching drawing knowledge and working on drawing tasks. The tutor system is designed to shorten the feedback times for both elements of the learning method during the learning process. A suitable concept for an artificially intelligent tutoring system addresses the educational needs of undergraduate students regarding different aspects of technical drawing. The tutor system is planned as a supplement to the existing didactic concept. In this context, educational needs refer to specific learning gaps that occur with the existing learning method. In order to define this concept, two questions need to be answered:

- What educational needs do students have regarding an intelligent tutoring system for technical drawing education?
- What capability does artificial intelligence provide in an intelligent tutoring system for technical drawing?

This publication aims to answer the first of these questions. Hypotheses for the second question will be defined qualitatively in order to propose a suitable concept. The capabilities of artificial intelligence regarding the tutoring concept will be estimated qualitatively on the basis of general AI capabilities. The detailed conceptualization and verification of AI capabilities is not included in this publication, because a prototype of the proposed concept needs to be implemented and tested in advance, since the use of AI is normally based on experiments (Blockeel and Vanschoren, 2007; Idowu et al., 2022). A second publication is planned to answer the question what capabilities AI provides regarding an intelligent tutoring system for technical drawings. Prior to the needs assessment of the online tutoring system, an analysis of the given educational concept for technical drawing skills is performed to answer the following question: "What do the students need to learn?" The learning materials of all current exercises on the associated course were examined for this purpose. The content framework of the tutorial system is set out on the basis of the collected learning materials. Knowledge elements are formed from the entire learning content using the knowledge that is necessary for correct processing of the tasks in the exercises. For example, it is necessary to be able to draw cut edges in accordance with standards in order to draw sectional views. The procedure for concept generation and evaluation is shown in Figure 1.

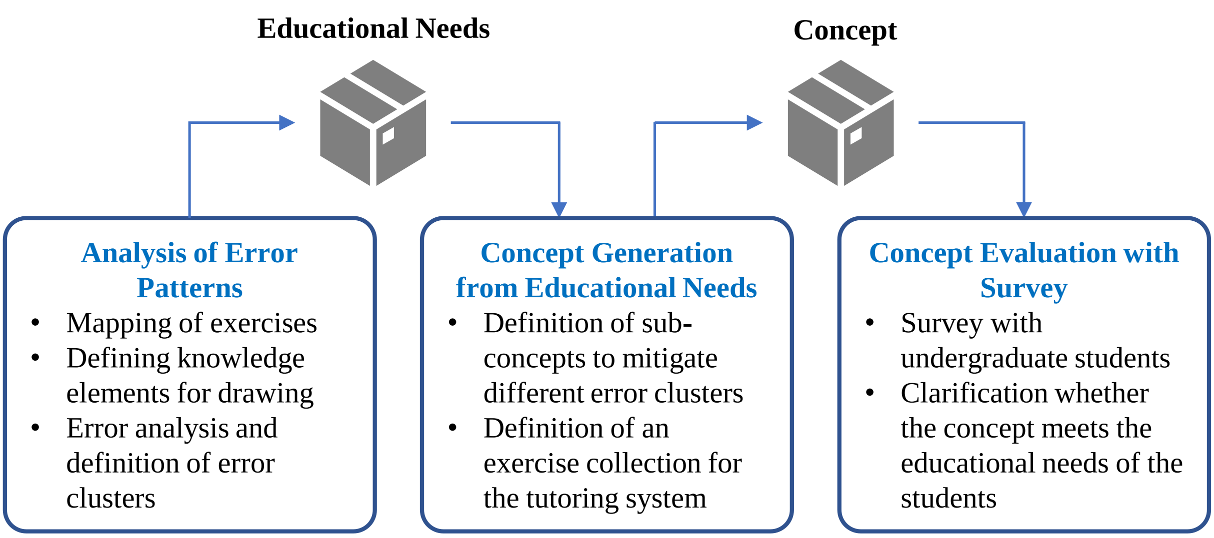

Figure 1. Research method

First, error patterns in the drawing exercises of the students are identified, analyzed, and interpreted. This step is intended to identify the subject-specific details for which students need additional support beyond the existing teaching concept. The identification of gaps in the established knowledge transfer raises the need for an additional support system. The data basis for this analysis comprises past drawing exercises that have already been edited and corrected. These drawing exercises currently fulfil the function of midterm exams within the semester. Students must pass these midterm exams in order to be admitted to the written exam. It is therefore expected that the students taking these midterm exams have already mastered the required learning content regarding technical drawing. For this reason, these drawing exercises in particular are suitable for identifying an educational need. If the errors in conventional exercises were to be analyzed and interpreted, it could not be assumed that there are actually educational deficits. Likewise, the learning process of the students could only be recorded at intermediate intervals before completion. Since midterm exams serve as a final element of individual students learning processes in isolated topics, this source of error can be eliminated. A total of 100 edited and corrected drawing exercises are analyzed. They are evenly distributed between the topics of views, sectional views, thread drawings, and assembly drawings. A points system with 10 evaluation categories is used to evaluate these drawing tasks. These act as error categories and form the basis for the error analysis. The error categories defined in greater detail for more accurate insights into student error patterns. Each error category is successively extended by different error types during the analysis if a previously unknown drawing error is found during the evaluation of an exercise. The concept of the resulting error table is shown in Figure 2.

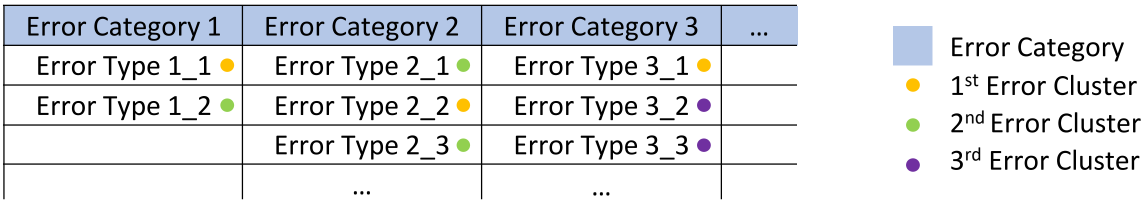

Figure 2. Error table

To better handle the large number of different error types, higher-level error clusters are formed. The decisive factor for assigning a fault type to a fault cluster is the question of what expertise is required to avoid the fault. The schema for assigning the error types based on competences is formed iteratively during the assignment process. The resulting structure of the error clusters with the subordinate error types and their frequency forms the result of the analysis phase. The extent to which the tutoring system covers the surveyed learning needs corresponds to the fulfilment of the functional requirements for the learning software. Non-functional requirements, such as system availability or data protection requirements, are already defined by the IKILeUS project application. Non-functional requirements are therefore not part of this publication. Systematic support for avoiding the identified error types and error clusters defines the educational need for learning support to be considered in the design of the tutoring system. The concept for the tutoring system is developed on the basis of this need. In addition, the capabilities of artificial intelligence to solve the support tasks are qualitatively assessed and integrated into the development of the concept. Not only does the concept define the capabilities and the process logic of the support system, it also specifies the available exercise collection and the user interfaces for students. The identified error clusters are covered by individual subsystems of the tutoring system. The error types are prioritized according to their relevance and covered by the individual exercises within the tutoring system. The result is the concept for the tutoring system and an associated exercise collection. The concept is then validated with respect to the needs that have been identified. A survey among students who have already taken the technical drawing modules is used for this step. They are asked to retrospectively assess whether the proposed concept would have helped them overcome their difficulties when learning technical drawing. In order for the survey results to be used in a targeted way, the survey begins with some general questions about the individual student and their previous knowledge of technical drawing. The concept for the IKILeUS system is then presented, as are the proposals generated for mitigating the error clusters. The students are asked what learning content should be available and what learning content is the most important for them. Alternatives to each subsystem of the tutoring system are presented for selection. Students are also given the opportunity to propose their own concepts, which helps ensure that the concept evaluation does not steer respondents too rigidly in a particular direction.

3. Results

For the analysis of the previous teaching concept, all 36 existing tasks for technical drawing were examined and 120 knowledge elements relating to technical drawing were collected from the examined learning materials. This knowledge is mandatory for the successful completion of the exercises. The analysis shows that the majority of technical drawing is taught in the first semester. Therefore, the tutoring system is also designed for use by first semester students. This focus offers some further advantages: Additional support is particularly useful in the first semester, as students are not yet as familiar with self-organized learning and can be assisted with online systems (Sharma and Fiedler, 2007). The number of students is also highest in the first semester, meaning that a tutoring system provides greater relief for the teachers on the associated courses. And since the drawing tasks in the first semester are relatively simple, the tutoring system can be expected to be more reliable when performing correction. During the content analysis of the previous teaching concept, focal points were identified for the following aspects of technical drawing: Drawing according to standards; Representation and projection of views; Creation of sectional views; Drawing of threads; Drawing of assemblies; Dimensions and tolerances. These topics cover the relevant basics of technical drawing, and the curricula of other learning materials for technical drawing are very similar (Leake and Goldstein, 2022; Labisch and Wählisch, 2020). This ensures that no relevant topics are left out. The selection of topics mentioned above is therefore used as a content framework for the design of the tutoring system. Based on this content analysis, the error patterns can be examined and the content requirements for the tutoring system can be surveyed.

3.1. Analysis of error patterns and elicitation of educational needs

In the analysis of the 100 submitted and corrected drawing tasks, a total of 134 error types were identified. The three exercises examined related to views and sections, thread drawings, and assembly drawings. A comparison with the surveyed knowledge elements ensures that these three tasks appropriately represent the variety of drawing tasks. For each of the 10 error categories per exercise, 62 error types are distributed in the exercise for views and sections, 40 error types in the exercise for bolts, and 32 error types in the exercise for assembly drawings. The identified error types differ in terms of the skills that students need to master in order to avoid them. The central question when evaluating the error types and forming the error clusters is which skills gap led to the occurrence of each error. After answering this question, the error types are iteratively grouped into error clusters based on similarities. The following three error clusters were created as a result:

- Faulty spatial thinking
- Faulty representation due to cursoriness and cleanliness errors
- Lack of theoretical knowledge of technical drawing

Necessary skills that students must master in order to avoid associated errors are therefore spatial thinking, knowledge of technical drawing rules and the ability to draw technical drawings completely and legibly. The first error cluster comprises drawing errors that are due to faulty spatial thinking, with typical error types in this cluster including missing circulating edges or chamfers. Projection errors between different views and sections are also common. In the second cluster are error types resulting from cursoriness and uncleanliness in the drawings. Errors in this cluster make it difficult to clearly recognise the geometry represented. The drawings are often incomplete or illegible. Examples are missing views and sections, unclean section hatching, and incorrect filling of the title block. The third error cluster relates to theoretical knowledge and contains drawing errors that are due to a lack of knowledge of rules and standards for technical drawing. Examples of such errors are cut representations of standard parts or the use of incorrect line thicknesses. Figure 3 provides a task-specific visualization of the distribution of errors among the individual clusters.

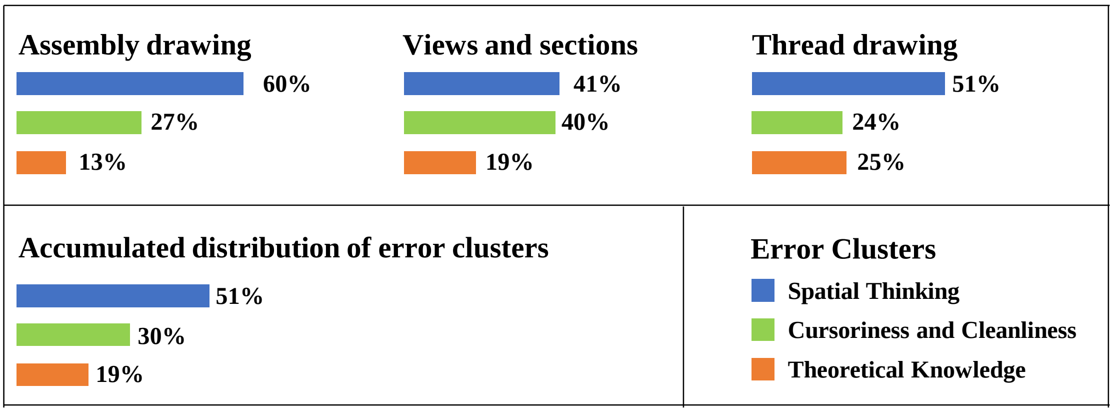

Figure 3. Distribution of the error clusters in different drawing tasks

Students make the most mistakes when seeking to correctly project geometric relationships. Geometric details, such as circulating edges, chamfers, and thread run-outs are often incorrect. Spatial reasoning errors are also common when creating sections and elevations. An average of 51% of the identified errors are due to poor spatial thinking skills. 30% of errors are due to cursoriness and lack of cleanliness in drawings, such as using incorrect dimensions or unclean section hatching. 19% of the errors are directly attributable to a lack of knowledge about the rules of technical drawing. The core requirement for the IKILeUS tutoring system is to close the identified skill gaps in the previous teaching concept through the expedient use of artificial intelligence. The analysis of the processed tasks makes it possible to divide this need into 3 error clusters with 134 error types. The content concept of the tutoring system must therefore be designed on the basis of these 3 error clusters and the specific tasks in the tutoring system must enable the examination of the different error types.

3.2. Concept generation for the tutoring system

The concept for the tutoring system consists of three modules, each covering one of the identified error clusters. Figure 4 outlines this concept. All subsystems can be used independently of each other by the students. There is no temporal causality in the application during the learning process. The first subsystem is designed to help students learn theoretical drawing knowledge, with the aim being to teach important drawing rules and norms. By using the corresponding functions, the students should be able to memorize the relevant knowledge. A pool with knowledge questions for memorization therefore seems appropriate. This is a common educational approach for acquiring relevant knowledge and is also appropriate for supporting spatial tasks like technical drawing (Hauptman 2010). A suitable knowledge base is formed by the 120 knowledge elements that were collected during the analysis of the previous teaching concept. These elements completely map the knowledge required for solving the drawing tasks and are at the same time compact enough to enable students to focus on the most essential drawing content in the first semester. In total, a collection of tasks with 120 knowledge questions is created to match the knowledge elements. These can be answered either as single choice, multiple choice, assignment tasks, or search box tasks. The multiple-choice and single-choice questions are designed to help students build up the necessary expertise through guided questioning with a predefined choice of solution options. In the context of the assignment tasks, students are shown a graphic with empty fields and a pool of terms or characters to be assigned using drag-and-drop. The purpose of search tasks is to train students in the use of tables. Questions in this category require students to search for appropriate table values for the problems covered in the particular assignment. In addition, it is possible to ask the questions without specifying an answer option in order to promote the memorization of knowledge. A history of answered questions is created and saved for each user. This shows which questions were answered correctly or incorrectly and at which frequency. With this database, artificial intelligence can be used to take on the role of a recommendation system for questions and to suggest the next question to be answered. Questions that are answered incorrectly more frequently are to be selected with a higher probability than questions that have already been answered correctly.

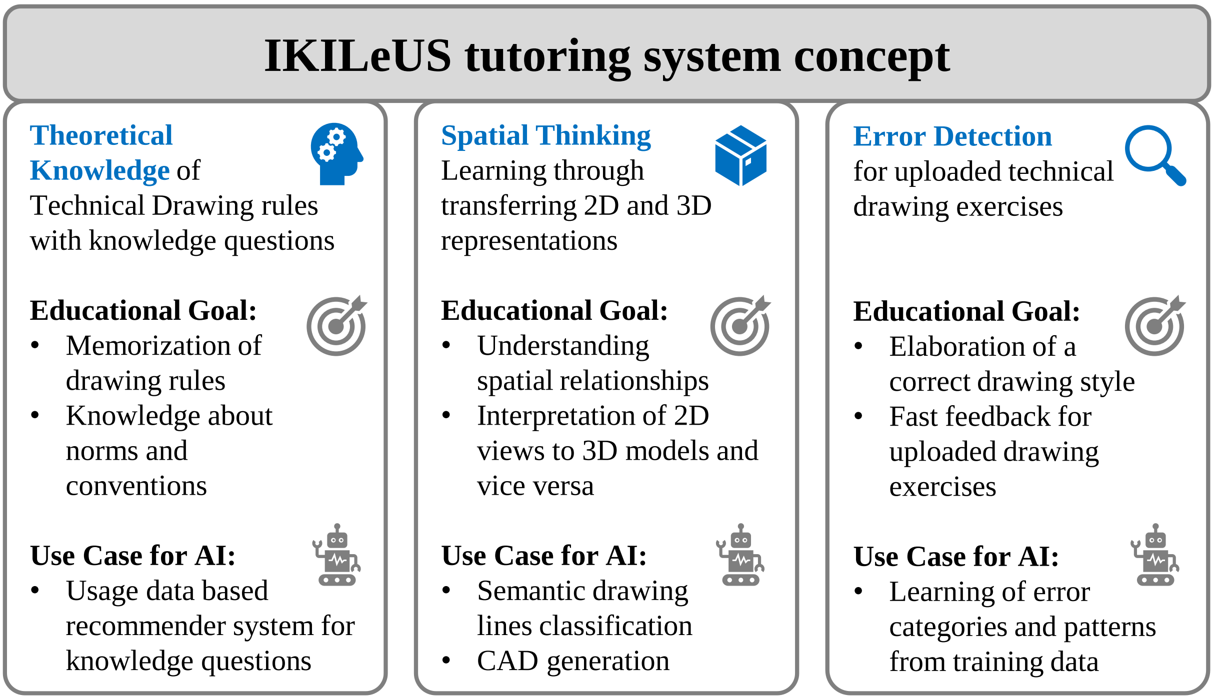

Figure 4. IKILeUS tutoring system concept

The second subsystem aims to train the students' perspectival and spatial thinking, with the plan being to teach the transfer of two-dimensional views to three-dimensional geometries and vice versa. The solution concept for learning spatial thinking is based on an AI-assisted conversion of 2D drawings into 3D CAD models. 3D manipulation, interactions with virtual models and a transfer from 2D to 3D are considered particularly suitable for training spatial thinking abilities (Kornkasem and Black, 2015; Münzer and Zadeh, 2016). Students are given the task of drawing a dimensioned axonometric view of a component as a three-panel projection. This three-panel projection forms the Input of the application. The drawing is converted to a CAD model using artificial intelligence and is then displayed to the students, with spatial volume differences between the nominal and actual values of the CAD model highlighted. The generated CAD model and the correct CAD model form the output of the algorithm and serves as feedback for the users. So, the student can compare both models to identify their errors. This gives students the opportunity to adjust their drawing without already knowing the sample solution. When transferring the axonometric representation or CAD model from the previous iteration to the three-panel projection, students learn the mental transfer from 3D space to 2D drawing – and when interpreting the CAD feedback, the transfer from 2D drawing to 3D space is reproduced. Overall, the exercise is therefore carried out in iterative cycles with a short feedback loop. For this part of the exercise, a collection of ten tasks that consist of drawings and CAD models, feature increasing levels of difficulty, and refer to the various knowledge elements has been generated. The suitability of these tasks for AI is ensured by a mathematical restriction of the geometric solution space during transfer. For example, only lines and circular arcs are allowed as two-dimensional basic geometries and the geometric dimensions can only take discrete values from an equidistant range of values in 2.5 mm increments. In addition, geometrically simple examples have been selected. AI might be expecially suited for the semantic processing of drawing lines (Seff et al., 2020). The third subsystem is intended to support students with exercises drawn from regular education. In this subsystem, students are able to upload their technical drawings from the regular drawing exercises and check them using the assistance system and the trained AI algorithms. The AI-supported subsystem should be able to check for carelessness errors and uncleanliness in the drawings, such as incorrect lines or incorrect title blocks. This service will enable students to receive feedback on possible errors before submitting their drawings as part of the regular course. The algorithms that evaluate the drawings and identify errors will follow classic machine learning approaches, such as convolutional neural networks. In order to keep the accuracy of the drawing evaluation as high as possible, several algorithms with different individual objectives are planned. For example, one algorithm extracts and evaluates the title block of the drawings by checking the individual components and comparing them with the respective task. Another algorithm evaluates the drawing lines with regard to correctness and completeness, identifying areas in the drawing that contain corresponding errors. As feedback, the students receive their drawing with annotations and localisations of errors. AI is used due to its capability of processing images like the uploaded drawings. It is not currently possible to quantify the exact number of algorithms that will be developed. This is due to the unpredictability of the quality of the respective algorithms depending on the resources available for the duration of the project. The exercise collection of this subsystem contains the existing exercises, as these have already proven themselves in practical use. A basic set of training data for these exercises is already available and will be expanded as part of the ongoing development of the tutoring system. The whole tutoring system is to be made available to students as an online service. Therefore, the input of drawing tasks as well as the feedback on their solution takes place via a website.

3.3. Evaluation of the concept with a survey

The aim of the survey is to find out whether the developed concept is considered useful from the user's point of view. Therefore, the key target group of the survey consists of students who have already attended the courses on technical drawing. This target group is able to retrospectively assess which form of support would have helped them in technical drawing. A total of 29 participants completed the survey. First, the educational goals of the individual subsystems were addressed with regard to their relevance and prioritization. Participants were then given the opportunity to name further educational goals that the system should cover. This is to clarify whether the error clusters surveyed and the need for a tutoring system identified in this way cover the actual need. The first question is intended to validate the overall concept with regard to user requirements. The second question provides information about which subsystem is particularly important for the students and should be focussed on accordingly for development. While multiple answers could be provided for the question relating to relevance, only single answers were permitted in response to the prioritization of learning content. The quantitative results are shown in Figure 5.

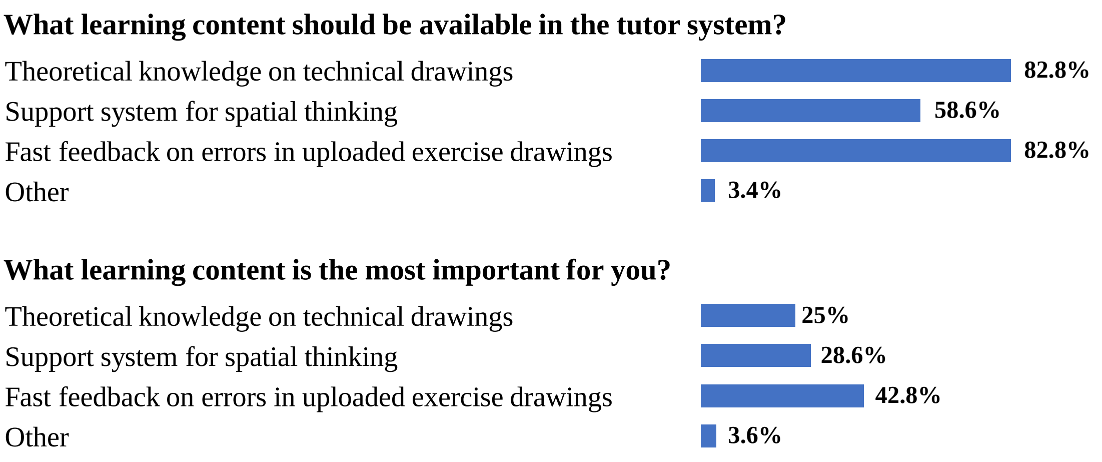

Figure 5. Survey questions on the different concepts

With regard to the different types of learning content, the aspects of error feedback and theoretical knowledge were selected most frequently with 82.2% each. 58.6% of the students would like support in relation to spatial thinking. Fast feedback on errors in drawing tasks was prioritized by 42.9% of participants, while 28.6% prioritized support for spatial thinking and 25% prioritized support for theoretical drawing knowledge. A small number of students would also have liked further learning support, but unfortunately did not provide any details via the text fields in the survey. The concepts of the individual subsystems are evaluated on the basis of these responses and the results are shown in Figure 6. In addition to the developed concept, alternatives are proposed and the participants are given the opportunity to suggest their own concept proposals for dealing with the individual error clusters.

These extended options help ensure that the survey does not steer students in a particular direction. The alternatives provided are video explanations for theoretical knowledge, assignment tasks for spatial thinking, and graphic error feedback. Multiple answers are possible for these questions. When it comes to addressing gaps in specialized knowledge relating to technical drawing, the suggested concept with the question catalogue enjoys broad support (58.6%). However, it should be supplemented by explanatory texts and illustrations, as 72.4% of the participants would like this. For the training of spatial thinking, participants can choose between two variants of the developed concept. The drawing input can be performed either via a graphical user interface on the end device or by scanning a paper drawing. In addition, the processing of assignment tasks for different perspectives of spatial bodies is suggested as an alternative. This is a common method for evaluating spatial thinking skills (Bednarz and Lee, 2011), but is not specific to technical drawing. All the concepts on spatial thinking received broad approval with results ranging from 51.7% to 58.6%. The proposed concept should therefore be pursued further. In addition, the theory questions can be extended by the addition of assignment tasks for spatial thinking. With regard to the correction of cleanliness and cursoriness errors, feedback based on the error categories is prioritized (75.9%). An approach based on the error categories of the assessment scheme should therefore be implemented. A small number of participants articulated a desire for other learning options, but did not provide any further detail in the text boxes.

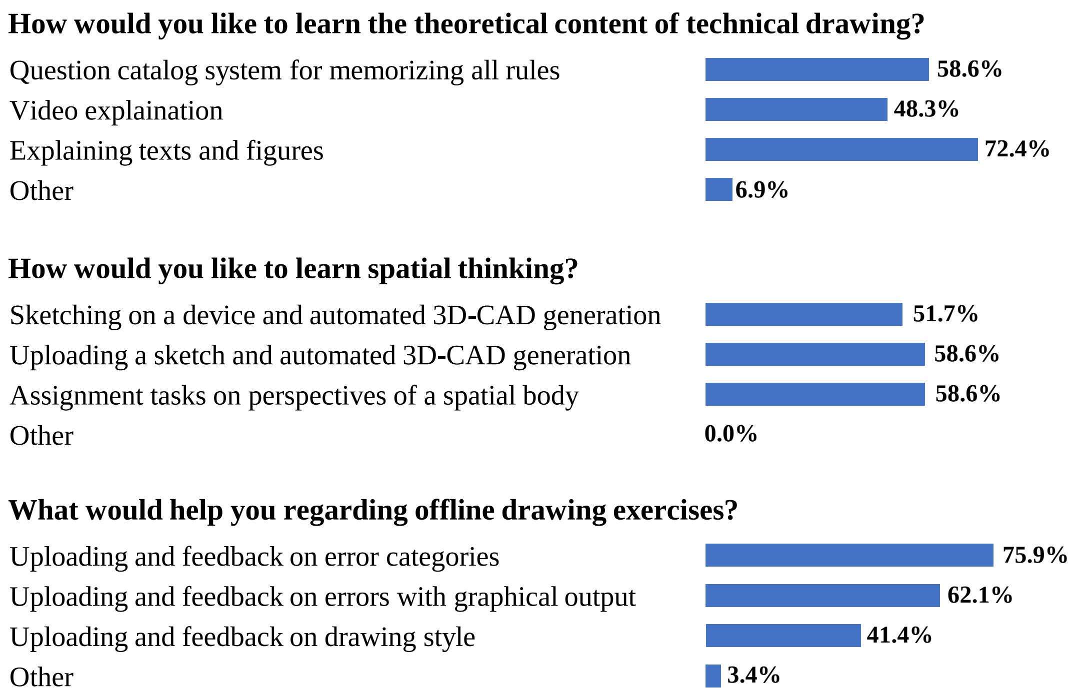

Figure 6. Survey questions on different versions of the concepts

4. Discussion

The following conclusions can be drawn for further steps. All three proposed subsystems of the tutoring system were confirmed by the survey. A question catalogue should therefore be used for learning theoretical drawing knowledge; this is enhanced by explanatory illustrations and texts for individual content. The developed concept is also pursued in relation to the improvement of spatial thinking skills. Input of scanned paper drawings is preferred, with input via a graphical user interface kept as a fall-back alternative because this is expected to enable easier processing by the AI. This is due to the fact that some steps for data pre-processing and semantic processing of the input data are omitted. Regarding the third subsystem, drawing correction is prioritized based on error categories. Overall, the defined concept for the tutoring system appears to meet the surveyed needs. The survey supports this conclusion because no conflicting requirements were expressed. Respondents were directly asked about additional learning needs and alternative concepts to serve the identified needs, and the answers they provided largely consisted of the identified needs and concepts. It must also be noted that the survey participants did not make use of the option to present individual needs or concepts. However, this must be contrasted with the fact that the defined sub-concepts are still relatively generic, since they cover an overall need. Further detail is then provided by the defect types and the associated tasks. It would be possible to conduct a further survey in order to validate the error types against the defined tasks and to ask the participants to specify the learning content that causes them problems. But since the initial learning of technical drawing was already two semesters ago for the students participating in the survey, these students can no longer be expected to provide a satisfactory answer to such detailed questions. A sample of students would have to be asked about individual drawing tasks immediately after the initial learning process. The generic character of the concepts also allows the hypothesis that few alternatives were suggested in the survey because there is little opportunity for them in terms of content. The error clusters and the sub-concepts cover an overall need in the learning process for technical drawing. Therefore, it is difficult to find technical drawing errors or learning content that cannot be assigned to any of the clusters. The assignment of individual error types to an error cluster is also not always clear-cut. This is due to the fact that analyzing a specific drawing error does not always lead to a doubt-free conclusion as to how exactly this error occurred. For example, if a section view is drawn incompletely, this may be due to a lack of expertise in representing sections. It is also possible that the student failed in the spatial projection of the section. It is also possible that the time allotted to the task was too short. The assignment to a cluster is based on the drawing context during the analysis. However, this ambiguity is not particularly critical for concept generation, since all defect types and defect clusters are covered by the defined concept. This could explain, for example, why there is a discrepancy between the frequency of spatial reasoning errors and the importance of this competence from the students' point of view. Another point that has not yet been answered quantitatively in the context of the presented study is to what extent AI is suitable for realizing the individual sub-concepts in an automated manner. The capabilities of AI were therefore only assessed qualitatively during concept development. The final answer to this question cannot be provided a priori for the implementation of the tutoring system, since the use of AI is strongly based on the performance of experiments and the quality of an AI model can only be predicted imprecisely.

5. Outlook

The existing teaching concept for technical drawing was analyzed and three error clusters were formed from 134 error types. A concept for a digital tutoring system to mitigate these error clusters was developed on the basis of this analysis. An exercise collection was created to match the individual error types. The overall concept was evaluated by a user survey and found to be suitable for matching existing educational needs. The tutoring system now needs to be implemented accordingly. Besides the development of a web-based user interface, the backend, a data pipeline, and a suitable software architecture, experiments must be conducted with a particular focus on the ability of artificial intelligence to implement the three subsystems. Training data that has already been gathered for the defined exercise collection will be used and extended for this purpose. It is expected that a hybrid use of artificial intelligence and conservative image processing algorithms will be used to implement the tutoring system. With regard to the industrial benefits, the algorithms for recognising errors in drawings could possibly also be used for the evaluation of drawings in companies. The conversion of three-panel projections to CAD models can facilitate the search for components in a CAD database for reuse by using a sketch of a component as input.

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